

Computer science

Case study: your (autonomous) taxi awaits you

For use in May 2018 and November 2018

Instructions to candidates

- Case study booklet required for higher level paper 3.

Introduction

We are in *Levangerstadt* at a moment in the near future. A text message tells us that our taxi is here. We climb into the car and give instructions about our destination. A friendly voice gives acknowledgment and the car moves off. But the voice does not come from the driver
 5 because there isn't one. In fact, none of the taxis in this town has a driver. *Autonomous* cars have arrived.

Figure 1: An example of “driving” an autonomous (self-driving) car



[Source: <http://nymag.com/selectall/2016/10/is-the-self-driving-car-un-american.html?>]

- Limited autonomy already features in many cars with functions such as adaptive cruise control, assistance in parking and traffic lane assist, but full autonomy, which would place the car at Level 5 on the *Society of Automotive Engineers'* scale, is now the goal of several companies.
- 10 These enterprises have been experimenting in this area over the last few years with the result that in several countries autonomous cars and taxis have been accepted on certain routes, but with one important proviso – that a human driver is present and ready to take over the controls. Neither legislators nor the public will accept fully-autonomous cars on the public roads unless they can prove that they have an exemplary safety record.
- 15 **Table 1**, on page 3, lists some of the companies that are at the forefront of the drive to introduce fully autonomous vehicles on the public highways. As indicated in the table, these companies are estimating that by around 2020 or 2021 the technology and associated systems will be sufficiently advanced as to permit this level of safe, autonomous driving. But will society be ready?

Table 1: Proposed introduction date of fully autonomous vehicles

Company	Plans	Proposed introduction date
Ford	Taxi services / ride sharing	2021 ¹
TESLA	Ride sharing	2020 ¹
Uber + Volvo	Taxi services	2021 ²
Google	Own fleet of vehicles	2020 ²
Drive.ai	Focus on end-to end learning	2020 ³

- 20 Technology is constantly evolving and it cannot be known for certain exactly which systems will be running these vehicles in the future. Nevertheless, this case study explores the technology and algorithms that are currently at the forefront of research into the development of autonomous vehicles through the plans being drawn up by the administrators of a fictional new town.

Levangerstadt

- 25 Sven Larsson is leading the technical team in charge of the *Levangerstadt* project. He outlined its aims:

- 30 “This is an ambitious plan for building a new town that will incorporate the latest technology in providing an environment that is safe both for the society that will live here and for the environment in which they will live. One fundamental policy will be the incorporation of autonomous vehicles as the only form of transport within the town’s boundaries.”

- 35 He went on to explain how car parks would be situated at all of the roads leading into the town where “normal” vehicles would be parked. Autonomous cars would function as taxis and could be summoned with the use of an app. Autonomous buses would run on improvised routes picking up customers on demand to take them to central places such as the shopping mall or the hospital.

Sven was clear about the many advantages:

- 40 “It has been estimated that human error contributes to 90 % of all traffic accidents. With the introduction of autonomous vehicles, we foresee a society in which traffic accidents are confined to the past, where traffic congestion is reduced and where there is a more productive use both of people’s time and of their local environment.”

Sven acknowledged, however, that there were potential problems still to be resolved.

“Although the prototypes have covered many thousands of miles, there are still situations in which they are not reliable enough and mistakes are made which could cost lives – situations in which a human driver would often react better.”

- 45 Sven went on to discuss the different technologies currently being tested as part of their project.

¹ <http://spectrum.ieee.org/transportation/advanced-cars/2017-the-year-of-selfdriving-cars-and-trucks>

² <http://www.businessinsider.com/how-uber-is-winning-when-it-comes-to-driverless-cars-2016-9>

³ <http://uk.businessinsider.com/driveai-using-deep-learning-for-its-autonomous-cars-2016-8>

Sensor Fusion

Sven explained how full autonomy depended upon achieving three basic functions at any moment in time:

- knowing the car's exact location
- 50 • being able to perceive the car's immediate environment
- making the correct driving decisions to get from A to B.

For safe driving the position of the car needs to be known to within a few centimetres. This requires a combination of GPS and high density (HD) mapping of the routes that will be used – neither of these on their own would suffice.⁴

- 55 *Sensor Fusion* provides the data, see **Figure 2**, for constructing a detailed picture of the immediate environment. A variety of sensors feed real-time data into the on-board control system which makes the driving decisions.

- 60 Light Detection And Ranging (LIDAR) is the primary contributor to this map through its construction of *point clouds*. This data is augmented through the use of radar, cameras, ultrasound and GPS, all of which have their specific purposes. HD mapping can also provide information about the route ahead.

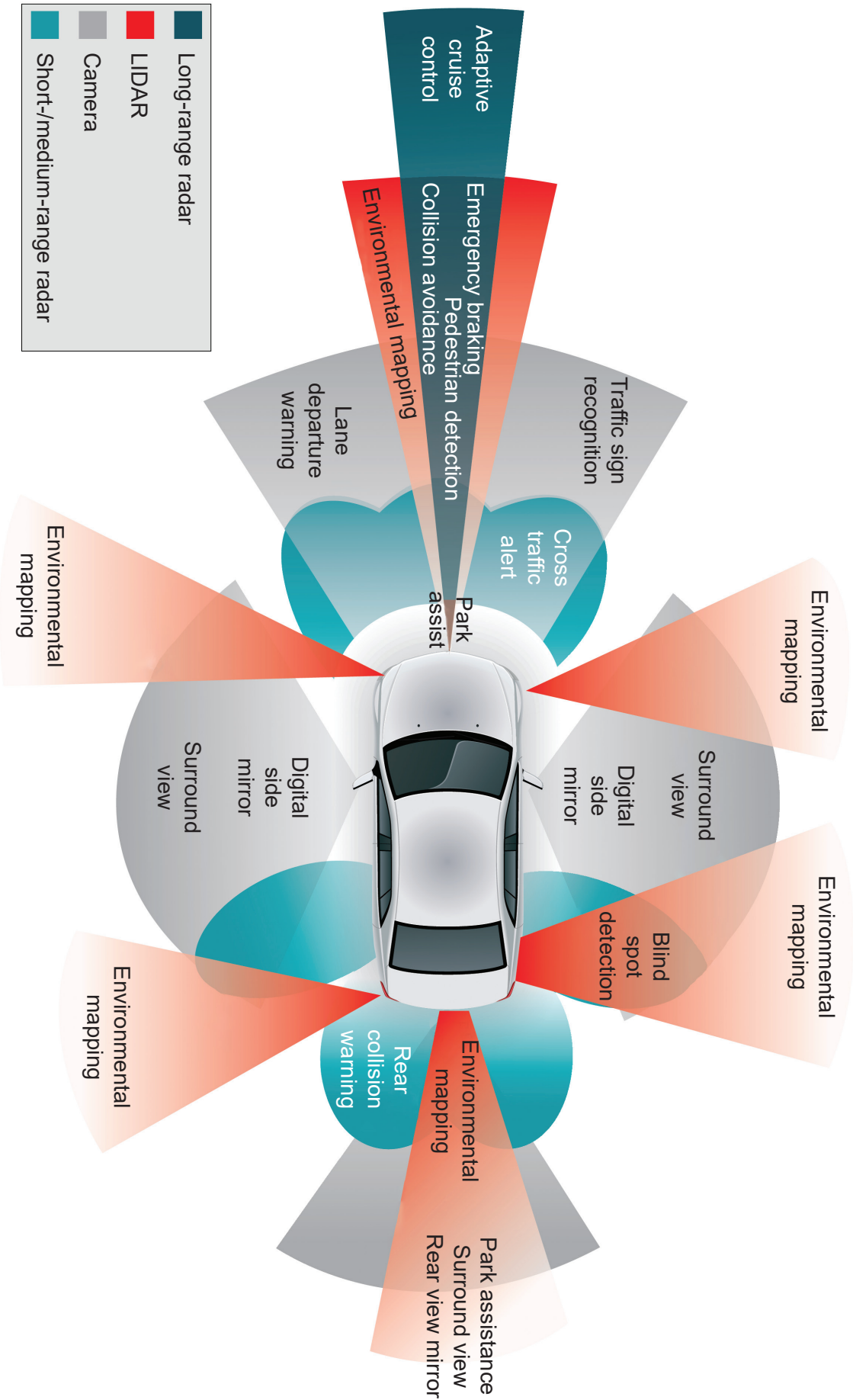
Sven pointed to the high cost both financially and in terms of computing power that this approach entails.

- 65 “Several times a second a complete 3-D map is constructed which must then be analysed by a computer system that must be compact and fast enough to be installed within each vehicle. When you consider that the vehicle only has two basic operations – adjusting the direction and adjusting the speed, it is clear that most of the data in this map will contain information that is not actually required. Equipment such as LIDAR significantly raises the unit price of each vehicle.”

- 70 Driving decisions are made after analysing the sensory data previously described. An area of computer science which is increasingly involved in the making of these decisions is *deep learning*. It is described in the next section.

⁴ <http://www.economist.com/news/science-and-technology/21696925-building-highly-detailed-maps-robotic-vehicles-autonomous-cars-reality>

Figure 2: An illustration of the data collected by Sensor Fusion



[Source: <https://roboticsandautomationnews.com/category/transportation/vehicular-automation/>]

Deep learning

Deep learning is a general term used in the field of *machine-learning* that refers to *artificial neural networks* that have many hidden layers.

- 75 The original neural networks, such as the *multi-layer perceptron (MLP)*, consist of an input layer, one or more hidden layers and an output layer. Each layer is fully connected to the next one. Although these networks have had success in solving problems in different fields, their limitations in the area of image recognition include the need for high processing power due to the cost of full connectivity, failure to use the relationships between points that are close to each other and a tendency towards *overfitting*.

This has led system software engineers towards the development of *convolutional neural networks (CNNs)* which are presently seen as an important component in meeting the 2020–2021 goals for autonomous driving.

- 85 Sven explained that they employed an IT company who would design the actual structure of the CNN, determine its initial parameters and carry out the training of the network. He emphasized, however, that his technical team should understand the basic features of a CNN and how each layer is created from the previous. He first described the different layers:
- the input layer, which for a colour image could be, for example, a $32 \times 32 \times 3$ pixel input plane (32×32 being the resolution of an image with 3 colour RGB colour channels)
 - 90 • the convolution layers, in which filters would search for certain features by moving through the image in steps (the length of each step set by the *stride* used)
 - the *feature maps* (one for each specific feature), which are produced as a result of the convolutions
 - the ReLU layers, which introduces non-linearity into the process – this helps with the training of these networks
 - 95 • the pooling layers, in which representative values are taken from one layer to form the next. *Max-pooling* is the specific technique used in this case study
 - the fully-connected layer, which then links all the features together
 - 100 • the output layer, which give a series of probabilities that the original image was a particular object.

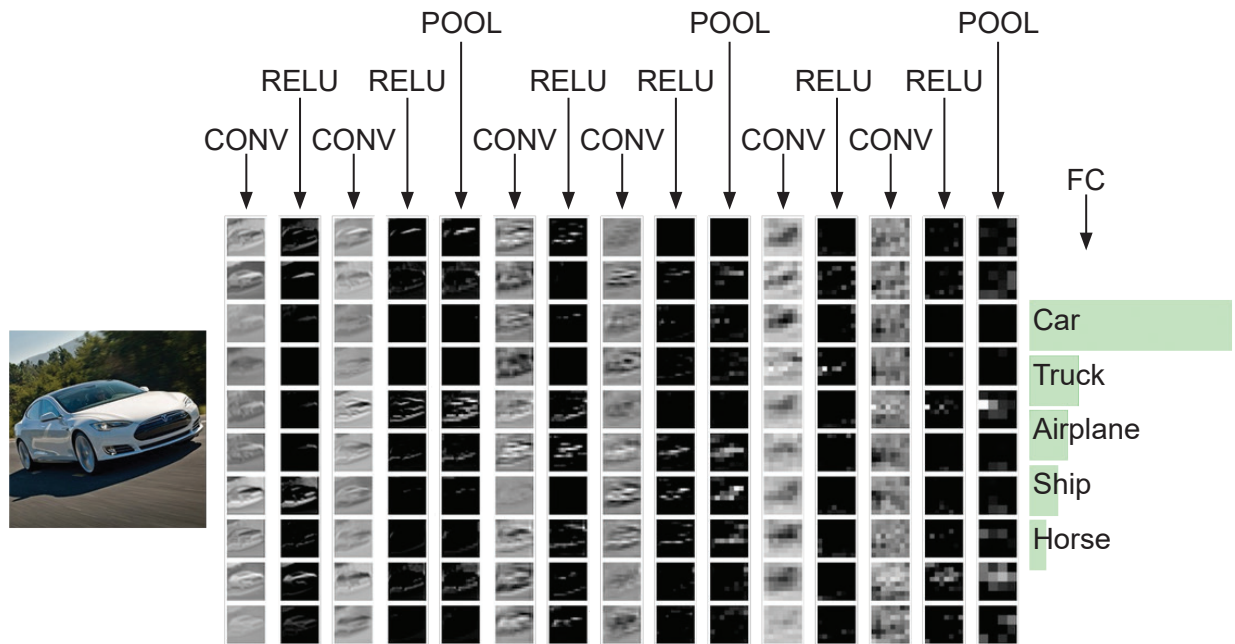
Sven stressed the importance of the convolutional process which is at the heart of the functioning of CNNs.

- 105 “In this process, the filter operates on each *receptive field* as it steps though the image thus creating the corresponding feature map. At each step, the value in the feature map results from the sum of the dot products of the corresponding values in the filter and the current receptive field.”

Sven summed up:

- 110 “CNNs allow the use of feature extraction through the passing of filters over the image to produce a stack of feature maps. There are as many filters and resulting feature maps as there are looked-for features. Initially the features would be basic ones, such as an edge or a curve. However, as we move through the CNN, the looked-for features will become more complex shapes.”

Figure 3: A typical example of the architecture of a CNN, showing the convolution (CONV), activation (RELU), pooling (POOL) and fully-connected (FC) layers



[Source: <http://cs231n.github.io/convolutional-networks/>]

He added that the advantages displayed by CNNs over more basic Artificial Neural Networks (ANNs) included:

- 115 • the property of *shift invariance*
- the reduction in the processing required due both to their basic design and to the use of *filter strides* and *pooling*
- the reduced memory footprint owing to the use of the same parameters (weights) across each convolution layer.

120 CNNs would not be able to be used either for training or for on-road testing if it wasn't for the latest developments in *Graphical Processing Units (GPUs)* and the availability of *large scale labelled data sets*.

Two particular areas in which modified CNNs are making an impact in research on autonomous driving are in object detection and *end-to-end learning*.

125 In the former, the data from the various sensors are fed into the CNN which then attempts to detect all objects of interest (particularly those in front of the car). These could be, for example, other cars, cyclists or pedestrians. The software will then put *bounding boxes* around these objects so that they can identify each image through the image recognition ability that the CNNs have already demonstrated themselves to have.

130 In this latter approach end-to-end learning is used in which the CNN learns appropriate steering movements by analysing these actions performed by human drivers over a variety of different routes. The only input received by the CNNs would be input from the front facing cameras. In its training mode, the CNN compares the action it would have taken with the action taken by the driver and through *backpropagation* repeatedly adjusts its parameters until the *cost function*

135 reaches an acceptable value.

Sven summed up the promise shown by the research into CNNs.

“It’s not possible to hard-code all the possible situations that a car might encounter. With extensive training CNNs should be able to make decisions on any situation encountered, even though we might not be able to determine ourselves the exact process that they went through.”

- 140 In working with established car makers, the *Levangerstadt* team was already beta-testing prototypes (with drivers present) on public roads in other parts of the country.

The Taxi Project

- 145 Both inhabitants and visitors would be able to download the *Levangerstadt* taxi app which when tapped would call the nearest available taxi. The taxi would then use an algorithm to plot the shortest route to the destination. The algorithm would make use of a digital map of the town where all of the major road intersections would form a set of nodes (n). The team is currently experimenting with *Dijkstra’s algorithm*. One concern for the technical team is that the efficiency of this algorithm in *BigO notation* often approximates to $O(n^2)$.

The Bus Project

- 150 The bus project was also discussed. The people living in the town would be able to use a similar app to summon driverless buses that would pick them up at specific locations and take them to the town centre. Each bus would work in a particular sector of the town and would calculate a new route each time it started a journey, again using the digital map previously described.
- 155 Determining a suitable route that will visit all of the required locations in the shortest possible time is basically a version of the travelling salesman problem. Originally the team considered using a *brute-force* approach that would calculate the length of each possible combination each time in order to choose the best, but this was found to be impractical. They are currently testing using the *nearest neighbour algorithm*, which being a *greedy algorithm* has its limitations.
- 160 Sven emphasized that as the project involved building a completely new environment, they would not only be able to embed the latest technology into the very fabric of the town, but at the same time avoid many of the problems associated with projects in which autonomous vehicles share the roads with cars driven by humans. All taxis and buses would then employ *vehicle-to-vehicle* (VTV) and *vehicle-to-infrastructure* (VTI) *protocols*. Sven believed that the
- 165 unique characteristics of the autonomous vehicles project would contribute greatly towards its success.

Sven emphasized that all members of the technical team were expected to understand the basic theory involved in the functioning of the path-finding algorithms being employed.

Social/ethical issues

- 170 Sven acknowledged that even when they were technically ready to go ahead, there were various ethical issues surrounding the concept of autonomous vehicles that had to be considered.

These included:

- the implications for jobs of enforcing a 100 % no-driver transport system
- the “Trolley Problem”
- 175 • the use of neural networks that produce solutions that we don’t really understand
- the beta-testing of autonomous car systems on public roads.

Challenges faced

The technical team must focus on the following challenges:

- to understand the basic functioning of CNNs as outlined in the case study
- 180 • to analyse and test the *nearest-neighbour* and *Dijkstra's algorithms* that have been considered for the bus and taxi projects
- to be able to respond to the social and ethical challenges to their project
- to incorporate appropriate technology throughout the town that would support their autonomous vehicles project.

Additional terminology to the guide

Autonomous
Backpropagation
BigO notation
Bounding boxes
Brute-force
Convolutional neural networks (CNNs)
Cost function
Deep learning
Dijkstra's algorithm
End-to-end learning
Feature maps (Activation maps)
Filters (Kernels)
Filter stride
Greedy algorithm
Machine learning
Max-pooling / Pooling
Multi-layer perceptron (MLP)
Nearest neighbour algorithm
Overfitting
Point clouds
Receptive field
Sensor Fusion
Society of Automotive Engineers
Shift invariance (Spatial invariance)
Vehicle-to-vehicle (VTV) protocol
Vehicle-to-infrastructure (VTI) protocol

Further reading/viewing

A demonstration of Dijkstra's algorithm:

- <http://optlab-server.sce.carleton.ca/POAnimations2007/DijkstrasAlgo.html>. Accessed 26 Apr 2017

An explanation of CNNs:

- <https://ujjwalkarn.me/2016/08/11/intuitive-explanation-convnets>. Accessed 26 Apr 2017

Lectures covering the basics of CNNs and autonomous vehicles: MIT January 2017

- <https://www.youtube.com/watch?v=1L0TKZQcUtA>. Accessed 26 Apr 2017
- <https://www.youtube.com/watch?v=U1toUkZw6VI>. Accessed 26 Apr 2017

Some companies, products, or individuals named in this case study are fictitious and any similarities with actual entities are purely coincidental.
